A methodology for snow data assimilation in a land surface model

Chaojiao Sun[1]
Hydrological Sciences Branch, Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Goddard Earth Sciences and Technology Center, University of Maryland Baltimore County, Baltimore, Maryland, USA

Jeffrey P. Walker
Department of Civil and Environmental Engineering, University of Melbourne, Parkville, Victoria, Australia

Paul R. Houser
Hydrological Sciences Branch, Laboratory for Hydrospheric Processes, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA

Received 11 May 2003; revised 4 March 2004; accepted 22 March 2004; published 27 April 2004.

[1] Snow cover has a large influence on heat fluxes between the land and atmosphere because of its high albedo and insulating thermal properties. Hence accurate snow representation in coupled land-ocean-atmosphere global climate models has the potential to greatly increase prediction accuracy. To this end, a one-dimensional extended Kalman filter analysis scheme has been developed to assimilate observed snow water equivalent into the NASA Seasonal-to-Interannual Prediction Project (NSIPP) catchment-based land surface model. This study presents the results from a set of data assimilation ''twin'' experiments using an uncoupled version of the land surface model. First, ''true'' snow states are generated by spinning-up the land surface model for 1987 using an observation-constrained version of the European Centre for Medium-Range Weather Forecasts (ECMWF) 15-year Re-Analysis (ERA-15) data set for atmospheric forcing. A degraded 1987 simulation was then made by initializing the model with no snow on 1 January 1987. A third simulation assimilated the synthetically generated snow water equivalent ''observations'' from the true simulation into the degraded simulation once a day. This study illustrates that by assimilating snow water equivalent observations, which are readily available from remote sensing satellites, other state variables (i.e., snow depth and temperature) can be retrieved and effects of poor initial conditions removed. Runoff and atmospheric flux predictions are also improved. *INDEX TERMS:* 1863 Hydrology: Snow and ice (1827); 3260 Mathematical Geophysics: Inverse theory; 3322 Meteorology and Atmospheric Dynamics: Land/atmosphere interactions; 3337 Meteorology and Atmospheric Dynamics: Numerical modeling and data assimilation; 3360 Meteorology and Atmospheric Dynamics: Remote sensing; *KEYWORDS:* snow assimilation, extended Kalman filter, GCM initialization

Citation: Sun, C., J. P. Walker, and P. R. Houser (2004), A methodology for snow data assimilation in a land surface model, *J. Geophys. Res.*, *109*, D08108, doi:10.1029/2003JD003765.

1. Introduction

1.1. Importance of Snow

[2] Snow plays an important role in governing the Earth's global energy and water budgets, as a result of its high albedo, low thermal conductivity, and considerable spatial and temporal variability [*Hall*, 1998]. Snow cover is one of the most highly varying hydrological quantities on the Earth's surface [*Gutzler and Rosen*, 1995], with the Northern Hemisphere mean monthly snow covered land area ranging from about 7% to 40% during the annual cycle [*Hall*, 1988]. Moreover, the energy demanded by snowmelt can significantly cool the surface and the overlying air [*Dewey*, 1977; *Namias*, 1985; *Baker et al.*, 1992; *Groisman et al.*, 1994]. Thus surface air temperature forecasts from numerical weather prediction are very sensitive to the snow cover extent and thickness. For example, improvement of snow physics in the NCEP (National Centers for Environmental Prediction) ETA operational forecast model substantially reduced a 2 m daytime air temperature cold bias for snow covered areas [*Mitchell et al.*, 2002]. Further, snow covered landscapes adjacent to bare soil regions have been found to produce mesoscale wind circulations [*Johnson et al.*, 1984] and snow cover variability has been shown to affect climate patterns in coupled climate simulations. Using

[1]Now at Global Modeling and Assimilation Office, NASA Goddard Space Flight Center, Greenbelt, Maryland, USA.

0148-0227/04/2003JD003765$09.00

the NESDIS (National Environmental Satellite, Data, and Information Service) snow cover data [*Robinson et al.*, 1993], *Cohen and Entekhabi* [1999] demonstrate that early season Eurasian snow cover variations are associated with dominant modes of midlatitude variability in the Northern Hemisphere winter. In addition, recent observational studies [*Lo and Clark*, 2002; *Bamzai and Shukla*, 1999] have shown an inverse relationship between antecedent snow mass or snow cover extent and Asian and North American summer monsoon intensity. Hence any long term coupled climate system prediction is dependent on accurate snow information.

[3] Because of its low thermal conductivity, snow can insulate the underlying soil and impede the depth and severity of soil freezing [*Lynch-Stieglitz*, 1994; *Sud and Mocko*, 1999]. While the energy balance is the primary driver of the Earth's atmospheric circulation system and associated climate, the water budget is also significantly modified through snowmelt processes. Being a medium-term water store, snow plays an important role in springtime runoff generation and flood production [*Hall*, 1988], and can provide a substantial component of the annual water budget. In many northern latitude regions (e.g., California), spring meltwater from the winter snowpack is the greatest source of water in the annual soil moisture budget [*Aguado*, 1985]. Therefore, to achieve accurate runoff and soil moisture prediction, which provides feedback to climate prediction [*Koster and Suarez*, 1995], it is important to accurately initialize snow cover in climate model forecasts.

1.2. Snow Observations

[4] Owing to considerable subgrid-scale spatial and temporal snow variability, and deficiencies in model snow physics, realistic global climate model snow prediction is difficult [*Liston et al.*, 1999]. Any land surface model initialization based solely on model spin-up will be affected by these problems. While there is a demonstrated need for routine snow observation (snow water equivalent, snow depth, snow temperature and hence snow cover), particularly for climate model initialization, routine ground-based snow observations are uncommon. In the United States, daily snow depth measurements are available at airports and from a network of volunteer observers. Snow course and SNOTEL (Snowpack Telemetry) sites collect more detailed snow data (snow depth, snow water equivalent and snow temperature), but these data are only collected in remote areas of the mountainous western states (information on SNOTEL can be found on the following Web site: http://www.wcc.nrcs.usda.gov/snotel/). In Canada, daily ground-based snow depth observations have been made at most synoptic stations since the 1950s, but the observing network is concentrated over the southern, more populated regions. Snow course observations are widely distributed throughout all of the provinces and territories, but they are made infrequently (weekly, biweekly or monthly) [*Brown et al.*, 2003]. Even though the in situ North American observations are among the best in the world, they are insufficient for global climate model initialization due to extreme snow depth heterogeneity.

[5] In contrast, remote sensing has the capability for providing snow information with the spatial coverage and temporal resolution needed for global climate model initialization. Remote sensing observations average out the small-scale variability inherent to in situ snow observations, therefore producing better climate-relevant snow information. Operational weekly snow cover analyses over North America have been produced from visible satellite observations by NOAA since 1966 [*Robinson et al.*, 1993]. Although this is the longest remotely sensed snow record available, it only provides the snow cover rather than snow mass information. While visible-infrared satellite sensors, such as the Moderate Resolution Imaging Spectroradiometer (MODIS) onboard Terra and Aqua currently provide the highest daily snow cover spatial resolution (500 m), they only work for cloud-free conditions. These high-resolution observations can provide information on fractional coverage of snow, which complements passive microwave observations that have coarser resolution, but fractional snow cover observation alone is difficult to use for quantitative snowpack initialization. Infrared sensors can also provide surface skin temperature information for cloud free areas. However, these temperature observations may not represent the surface snow temperature, especially when vegetation protrudes above the snowpack. When high-resolution snow cover and surface skin temperature observations are used together with snow mass observations from passive microwave sensors, synergistic benefits may be derived for estimating snowpack states. Since research-quality data sets of simultaneous snow cover, snow depth, and snow water equivalent observations are still under development [*Robinson*, 2002], we focus on using passive microwave observations in this study.

6. Conclusions

[40] A methodology for generating global climate model snowpack initialization that does not rely on land surface model spin-up has been described. This methodology produces the snowpack states by assimilating total snow water equivalent observations using the extended Kalman filter. A series of numerical experiments using this methodology illustrate that snowpack states (snow water equivalent, snow depth and snow temperature/heat content) may be retrieved from total snow water equivalent observations which are readily available from passive microwave remote sensing. Moreover, the effect of snowpack forecast errors on the energy and water balance (i.e., evapotranspiration, runoff and both upward longwave and shortwave radiation) has been demonstrated, with the assimilation having a significant positive impact on these flux estimates.

[41] This study has demonstrated that by assimilating total snow water equivalent observations using the extended Kalman filter, and reconstructing the other prognostic snow states (snow depth and heat content) through the use of diagnostic model variables (snow density and temperature), all snowpack prognostic variables can be retrieved efficiently. This is because snow water equivalent is highly correlated with snow depth and heat content, while independent of snow density and temperature. It should be noted that this twin experiment has not accounted for model simulation or observation biases, even though they are often inevitable in reality. This important issue is beyond the scope of the current paper, and is an important future research topic.